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The estimation of regional cereal yields

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1. Introduction

Certain advantages accrue if the Regional or National cereal yields can be estimated accurately at harvest time, or predicted some time in advance of harvesting. Such information is of considerable value in determining as early as possible the likely quantities of grain to be stored, imported and exported during the following year, and in arranging the necessary facilities and transactions early enough to obtain some national economic advantage. Yield alone is not sufficient to determine all the required information: quality must also be known to estimate for example the quantity of hard milling wheat to be imported, or the likely export market for malting barley. A knowledge of likely yields in other countries is of great importance for major exporters such as the USA which have to judge each year the size of the world market, organise shipping, export and import credit, and determine pricing policy accordingly.

Most of the variations of yield (expressed as tonnes/ha) from year to year are the result, directly or indirectly, of weather. Weather plays its part in determining the effectiveness of soil preparations and the timelyness of drilling. Weather controls the rate of development of the crop, the time of onset of senescence, the amount of radiation the crop intercepts and the effects of diseases in reducing plant vigour and yield. Finally it determines the success of harvesting. Crops respond then to their climate at most stages of their growth. In these circumstances it is possible in principle to model the whole period of crop development from sowing to harvesting in terms of suitable meteorological variables, and to finish up with a yield estimate. Such estimates are especially useful for economic strategies when their dependance on weather in the later stages of growth is relatively small so that useful yield forecasts can be made some time before harvest.

Many papers and publications report relationships between cereal yields and weather. Baier (1977) has reviewed the main types of model suitable for yield assessment and distinguishes between two general classes of model

(i) Crop-growth simulation

(ii) Empirical-statistical (crop-weather analysis)
  (a) Factorial
  (b) Simple multiple regression

Models of class (i) attempt to simulate the entire response of the plant to the environment, by including the physical, chemical and physiological processes which contribute to plant development. They may therefore be used in principle to model the growth and yield of crops in any climate zone. Such models are necessarily elaborate (for example those of de Wit et al (1971) and Shawcroft et al (1974)) and are not suited to the calculation

of Regional yields on a routine basis, in spite of their present complexity, because they are still inadequate to represent all the relevant and interacting processes occurring through the whole growth season. Much-simplified photosynthesis models (eg Hough 1978) fall partly into this class but cannot be used for yield estimation without a considerable empirical input.

Models in class (ii) (a) involve the product of two or more factors which each represent a simplified relation between a plant response (in this case yield) and variations in meteorological inputs at different growth stages. They require less-detailed data than model of class (i) and are better suited to the description of yields in terms of standard climatological observations. An example is given by Baier (1973) which analyses the daily contributions to final yield of up to three agro-meteorological variables, using biometeorological rather than secular time. The third type of model (class (ii) (b)) is essentially a more empirical version of (ii) (a) in which (less realistically) several variables which usually represent weather and soil conditions are related to yield additively: the regression coefficients are determined by standard statistical methods, in this case usually multiple linear regression. This type of model is often applied to the specification of year-to-year yield variations at individual sites, but the coefficient values often vary widely between different sites, emphasising the empirical nature of the models. A further difficulty is that the variables used such as temperature, rainfall and sunshine are not independent. In these circumstances Marquina (1979) has pointed out that the estimates for the regression coefficients are highly unstable. The addition of only one extra year's data to a historical sequence and reworking of the regression analysis can result in regression coefficients which change not only in size but sometimes in sign as well.

One of the advantages of models of class (ii) (a) is that they are well-suited to showing at any time during crop development the influence of past and current weather on future expected yield. They can provide therefore estimates of final yield before harvest by using for example climatological averages for data between cut-off time and date of harvest (eg Robertson 1974). However they involve the empirical determination of a large number of regression coefficients, which can only be done successfully if very long-term homogeneous yield records are available, and probably phenological data also: "homogeneous" in this sense implies only minor variations in cultivation practices through the whole period studied, a situation achieved only in special research trials, for example the Broadbalk experiments at Rothamsted, and the Swift Current (Canada) series used by Robertson.

Much of the yield modelling has been carried out in America where year-to-year fluctuations in yield are often relatively large. In these circumstances relations between yield and suitable weather variables can often be identified readily and shown to account for a considerable proportion of the yield variations. In the United Kingdom the situation is less clear-cut. The yields shown relatively small variations from year-to-year and it is harder to isolate therefore the weather factors of most importance in controlling yield. Table 1 shows wheat and barley yields for West Midlands and East Regions for 24 years, as extracted from the Agricultural Statistics for England and Wales (HMSO) (Yields for all 8 regions are given in Appendix 1). They display a generally rising trend, due presumably to improvements in varieties, and better husbandry (eg higher fertiliser applications, more timely field operations, better pest and disease control). They also show a marked upturn in yield after 1961. This was commented on by Smith (1974a, b) who suggested that the 1962 yields were unrealistically high in view of the "mediocre" weather that year: he proposed that the method used in yield assessment must have changed between 1961 and 1962.

Table 1 Wheat and barley yields, West Midlands and East Regions

Year	Wheat (t/ha)		Barley (t/ha)	
	West Midlands	East	West Midlands	East
1950	2.54	2.67	2.43	2.52
51	2.60	3.02	2.53	2.56
52	2.63	3.11	2.56	2.36
53	2.91	3.21	2.76	2.88
54	2.55	3.23	2.67	2.91
55	2.78	3.76	2.83	3.19
56	2.98	3.38	2.88	3.05
57	2.84	3.54	2.58	2.78
58	2.95	3.34	2.85	2.97
59	3.24	3.78	3.17	3.15
60	3.44	3.73	3.29	3.09
61	3.39	3.53	3.28	3.03
62	4.21	4.63	3.65	3.62
63	3.86	4.16	3.65	3.67
64	4.11	4.29	3.75	3.74
65	3.98	4.20	3.77	3.93
66	3.66	4.04	3.59	3.69
67	3.95	4.25	3.74	3.65
68	3.36	3.48	3.45	3.37
69	3.86	4.01	3.39	3.54
70	4.24	4.09	3.43	3.06
71	4.25	4.55	3.92	3.33
72	3.87	4.55	3.90	4.07
73	4.34	4.41	3.92	3.88

This is a point of considerable importance if attempts are made to develop statistical relationships between historical yields and weather, with the results being used to estimate yields in following years. Moles (1971) reviewed the various methods used to estimate cereal yields in England and Wales. He commented on the relatively low accuracy achieved in pre-harvest yield estimation by MAFF crop-reporting, with evidence for bias in the more exceptional years - overestimation in poor years and underestimation in years with high yields. In particular the "end of harvest" estimates published in the HMSO Agricultural Statistics showed the same bias when compared with the more accurate estimates (for wheat only) obtained through the Cereal Deficiency Payment scheme up to 1970: after 1970 the CDP scheme was run on a basis providing less accurate wheat yield figures. He also noted that from 1962 onwards the official statistics showed a change in emphasis in favour of the CDP estimates, partly in accord with Smith's comments, although the CDP estimates also showed a marked increase in 1962. Table 2 (from Baines 1966) compares the National wheat yields with those from the CDP scheme for the period 1957 - 1964. The average difference between the two sets of yield estimates prior to 1962 was .11t/ha, or about 3%. It seems likely that differences on a regional basis would be larger than this.

Table 2 Wheat yields, England and Wales (t/ha)

Year	Official Estimate	CDP estimate
1957	3.18	3.10
1958	3.07	2.87
1959	3.61	3.54
1960	3.56	3.63
1961	3.53	3.41
1962	4.37	4.35
1963	3.93	3.85
1964	4.23	4.22

Thus it is likely that there are errors, probably of the order of 5%, in regional yield estimates prior to 1962 (and probably after 1970 when the CDP scheme was withdrawn).

Table 3 shows departures in yield from linear trend lines fitted to the data for the 24-year periods, for the two crops and two regions of Table 1, and the results after normalising these departures to 1950 levels of technology: the latter presumably are required if the effects on yield due to technological changes are to be minimised.

Table 3 Departure of annual yields from linear trend [(c)] over 24 years

Year	Wheat				Barley			
	West Midlands		East		West Midlands		East	
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
1950	0	0	-.38	-.38	-.08	-.08	-.12	-.12
51	-.01	-.01	-.10	-.10	-.04	-.04	-.14	-.14
52	-.06	-.06	-.07	-.07	-.08	-.08	-.39	-.37
53	.14	.13	-.03	-.03	.05	.05	.08	.08
54	-.30	-.27	-.08	-.07	-.10	-.09	.05	.05
55	-.15	-.13	.39	.35	0	0	.27	.24
56	-.03	-.03	-.06	-.05	-.02	-.02	.07	.06
57	-.25	-.20	.04	.03	-.39	-.33	-.25	-.22
58	-.21	-.17	-.23	-.20	-.18	-.15	-.12	-.10
59	0	0	.15	.13	.06	.05	0	0
60	.12	.09	.04	.03	.13	.10	-.10	-.08
61	-.01	-.01	-.23	-.19	.05	.04	-.23	-.19
62	.73	.53	.81	.65	.36	.27	.30	.24
63	.30	.21	.27	.21	.30	.22	.30	.24
64	.47	.33	.34	.26	.33	.24	.31	.24
65	.27	.18	.19	.14	.28	.20	.44	.33
66	-.13	-.09	-.04	-.03	.04	.03	.15	.11
67	.08	.05	.11	.08	.13	.09	.05	.03
68	-.59	-.38	-.73	-.53	-.23	-.16	-.28	-.20
69	-.17	-.11	-.26	-.19	-.38	-.25	-.17	-.12
70	.13	.08	-.25	-.18	-.38	-.25	-.70	-.49

71	.07	.04	.15	.10	.05	.03	-.49	-.34
72	-.39	-.23	.09	.06	-.04	-.03	.19	.13
73	0	0	-.12	-.08	-.09	-.06	-.06	-.04
RMS deviation		.20		.24		.15		.21

(a) Uncorrected departure
(b) Corrected to 1950 yields given by trend line
(c) Wheat: West Midlands Yield = 2.54 + .078 x year (0 ≡ 1950)
East Yield = 3.05 + .064 x year
Barley: West Midlands Yield = 2.51 + .065 x year
East Yield = 2.64 + .054 x year

The root mean square values of the normalised departures represent coefficients of variation between 0.06 and 0.08 but these may be exaggerated by the presumed spurious fluctuation introduced by the changed method of yield estimation introduced after 1962. Table 4 gives therefore the results of a similar analysis carried out after sub-dividing into the periods 1950 - 1961 and 1962 - 1973. The coefficients of variation now lie in the range 0.04 to 0.08 and are generally smaller in the first 12-year period.

Table 4 Departure of annual yields from linear trend lines (c) over 12-year periods

Year	Wheat				Barley			
	West Midlands		East		West Midlands		East	
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
1950	.07	.07	-.27	-.27	.01	.01	-.05	-.05
51	.05	.05	0	0	.04	.04	-.07	-.07
52	0	0	.02	.02	0	0	-.32	-.31
53	.20	.18	.04	.04	.12	.11	.14	.13
54	-.24	-.20	-.01	-.01	-.04	-.04	.12	.11
55	-.08	-.07	.44	.39	.05	.04	.34	.31
56	.04	.03	-.02	-.02	.03	.03	.15	.13
57	-.18	-.15	.07	.06	-.34	-.28	-.18	-.16
58	-.15	-.11	-.21	-.17	-.15	-.12	-.04	-.03
59	.06	.05	.16	.13	.10	.08	.08	.07
60	.18	.15	.03	.03	.15	.12	-.03	-.02
61	.05	.04	-.25	-.19	.07	.05	-.15	-.12
r.m.s deviation		.10		.17		.11		.16
1962	.31	.31	.44	.44	.05	.05	-.03	-.03
63	-.05	-.05	-.04	-.04	.04	.04	.02	.02
64	.18	.18	.09	.09	.12	.12	.10	.10
65	.03	.03	-.01	-.01	.13	.13	.30	.30
66	-.29	-.29	-.17	-.17	-.06	-.06	.06	.06
67	-.02	-.02	.03	.03	.07	.07	.02	.02
68	-.62	-.61	-.74	-.73	-.23	-.22	-.25	-.25
69	-.13	-.13	-.22	-.22	-.30	-.29	-.07	-.07
70	.23	.22	-.14	-.14	-.27	-.26	-.56	-.57
71	.23	.22	.31	.31	.20	.19	-.28	-.28
72	-.16	-.15	.30	.30	.17	.16	.47	.48
73	.29	.28	.16	.16	.18	.17	.29	.29
r.m.s deviation		.26		.31		.17		.28

(a) Uncorrected departures
(b) Corrected to 1950 or 1962 yields given by trend lines
(c)

Wheat:	West Midlands	1950 - 61	Yield = 2.47 + 0.078 x year	(r = .90)
	East	1950 - 61	Yield = 3.05 + 0.064 x year	(r = .84)
	West Midlands	1962 - 73	Yield = 3.90 + 0.013 x year	(r = .17)
	East	1962 - 73	Yield = 4.19 + 0.006 x year	(r = .06)
Barley:	West Midlands	1950 - 61	Yield = 2.42 + 0.072 x year	(r = .89)
	East	1950 - 61	Yield = 2.57 + 0.055 x year	(r = .75)
	West Midlands	1962 - 73	Yield = 3.60 + 0.013 x year	(r = .26)
	East	1962 - 73	Yield = 3.65 - 0.005 x year	(r = -.07)

Yield fluctuations appear to be larger in East Region than the West Midlands. It is significant that the calculated trends are small in the second 12-year period. Unpublished NIAB data show that the main winter wheat variety used in the United Kingdom over this latter period was Capelle Desprez, which accounted for between 30 and 65% of the combined total of winter and spring wheat sown in each of the 12 years. In the period 1969 - 1972 Joss Cambier comprised between 10 and 32% of the total sown, and this variety was found to outyield Capelle by about 10%. There was no other widely-sown high-yielding variety introduced in the period. The main spring varieties were first Jufy, then Opal, Kloka and Kolibri, with a progressive yield increase of about 15%, associated mainly with Kolibri: however the hectarage sown to the last did not exceed 11% of the total wheat sown in any year. Table 5 gives results extracted from seeds sales data for the United Kingdom for a number of years. The data are to some extent fragmentary and their interpretation

Table 5 Winter wheat and winter barley sales expressed as percentage of combined winter and spring varieties.

Harvest year	Wheat			Barley		
	West Mids.	East	UK	West Mids.	East	UK
1959	53	66	47	6	6	5
60	75	85	67	13	9	7
61	39	52	-	9	8	-
62	74	65	66	8	4	-
63	77	78	-	8	9	-
64	76	79	-	8	7	-
65	72	86	-	12	7	-
66	68	69	-	5	7	-
67	66	67	-	6	11	-
68	67	82	-	7	11	-
69	77	71	-	9	8	-
70			-			-
71			95			9
72			94			9
73			-			-
74			92			10
75			89			10
76			96			14
77			94			13

is not altogether clear: it is not certain for example that the seed of a winter variety is always drilled in the year it was purchased. However the data suggest that there have been marked variations in the ratio of winter to spring wheats drilled each year up to the end of the 1960's: since then

by far larger proportion of wheat has been the winter varieties. By contrast the proportions of winter barley have nearly always been less than 10% until the mid-1970's. Winter cereals usually yield higher than those which are spring-sown but this, at least until very recently, has been of negligible significance in the total barley yields. Table 5 suggests that the proportion sown to winter wheat increased sharply by the end of the second 12-year period. A trend therefore is expected to be seen in the wheat yields over the period. The calculated trend is very small (Table 4). The nationwide data for spring barley showed Proctor (46% of combined total) and Rika (26%) as the main varieties in 1962. The proportion sown to Proctor became negligible by 1973 (8%) and negligible for Rika by 1968, with the replacement varieties being first Pallas, then Zephyr, Sultan and Julia. However in 1973 only Julia (26%) exceeded 10% of the total. Julia gives yields about 10% higher than Proctor and Rika (NIAB trials data) and so some upward trend in the barley yields as well as the wheat yields would have been expected in 1962 - 1973 (the very high input cereal farming which is now widely practiced, involving heavy fertilizer applications and rigorous spray programmes to produce high yields has been a feature of recent years but probably would have made only a small impact in the early 1970's). Table 4 shows that 10 of the 12 yields listed for the final 3 years 1971 - 1973 lay above the trend lines (which would occur randomly with a probability of 1 in 60) and this suggests that the trend lines may be biassed to some extent, for example by the very high yields in the early sixties.

The evidence then is for a considerable random component in the regional yield figures. This is unfortunate, because in order to develop useful methods of estimating regional yields by regression on meteorological variables it is necessary to use published yields over say 10 or 15 recent years to develop suitable regression relations which then have to be tested against independent data from very recent years to demonstrate their utility. An indication of the "noise" in the 12-year sets of yield data may be obtained by finding the correlation between the West Midlands and East Region yields after correction for trend, and normalisation. This implies the plausible assumption that the major influences of weather on yield in particular years are likely to have affected results from both Regions to similar extents. The correlation coefficients are given in Table 6. Those for the earlier period are discouragingly small and suggest that it will be difficult to develop useful

Table 6 Correlation of West Midlands and East Region yields

Period	Wheat	Barley
1950 - 1961	-.11	.35
1962 - 1973	.69	.63

relations between yield and weather using the present data sets. The much higher values for the second period provide some encouragement, although as discussed earlier they may result in part from difficulties in trend removal.

2. Model variables

Yields are assumed to be represented by the multiple linear regression relationship

$$Y_c(t) = a_0 + \sum_{t=0}^{N-1} a_i X_i(t) \qquad (1)$$

where

t = year

$$Y_c(t) = \left(Y(t) - Y_{trend}(t)\right) \cdot \frac{Y_{trend}(o)}{Y_{trend}(t)} \qquad (2)$$

$Y(t)$ = yield in year t

$Y_{trend}(t)$ = estimated yield in year t obtained from linear trend line fitted to yield data from years $t=0$ to $t = N-1$

$Y_c(t)$ = departure of yield from linear trend line in year t, normalised to a standard yield (that in year 0 obtained from the trend line)

$X_i(t)$ = i^{th} variable

a_i = i^{th} linear regression coefficient

The choice of variables should strictly reflect the response of the crop to its environment at all its growth stages. In practice this is not possible in the present cases because the number of years of yield data is small and so only a small number of "independent" data can be used if overfitting is to be avoided. Gallagher and Biscoe (1978) showed that for both wheat and barley there were close relations between radiation intercepted by the crops over the growth season and total dry matter production, provided the crop was not subjected to drought stress. The harvest indices (ratio of grain weight to total dry matter weight) showed generally small variations unless the crop was severely stressed in the later stages. Gallagher et al (1976) considered two sources of assimilate supply for grain growth: photosynthesis after anthesis, and translocation of materials assimilated before anthesis and temporarily stored before moving to the grain. They found that during an extreme drought year (1976) when grain growth stopped very early the latter source provided nearly 60% of the final grain dry matter in wheat compared to 20% or less in more normal years (Thorne 1966). The short duration of grain growth during this year is consistent with observations by Ford et al (1976) which showed that high temperatures reduced the period of grain growth, and also reduced slightly the number of grains. Gallagher et al (1975) found in the case of barley under severe drought conditions that up to 70% of the final grain weight was attributable to translocation of materials assimilated before anthesis: under more normal conditions the figure appears to be similar to that for wheat (20% or less). In most years except the droughts with their high temperatures the final grain weights of barley are relatively stable, due to the compensating effects of translocation (Gallagher et al 1975) and so yield variations from year to year are in most years primarily related to variations of grain numbers per square metre. On these bases years with high yields require high dry matter accumulation during the period when dry matter accumulation is most rapid (up to around anthesis) followed by a grain-filling period without very high temperatures so that it is not shortened by premature senescence. It is important therefore that the crop establishes a large leaf area and maintains it through May, June and July when radiation levels are large. It is obviously important that the crop remains disease-free to maintain maximum photosynthesis and effective grain filling.

The duration of the periods between particular growth stages of the cereals

may be expressed approximately in terms of number of day-degrees above a certain temperature base (usually around 5 deg C) (Nuttensen 1955, 1957). Consequently cool seasons will generally be favourable to long duration of green leaf area, late senescence and hence potentially higher radiation interception. Against this the cool season is often associated with lower radiation levels.

Drought is significant for any crop in two ways. First the high soil moisture deficits cause restricted stomatal opening and hence reduce the supply of CO2 to the plants, as well as restricting the uptake of nutrients from the soil. Secondly, and of particular importance to the cereals which mature well within the growing season, a drought-stressed crop is significantly warmer than one freely supplied with water. For example Thompson (1978) showed that a mature cereal canopy under severe stress in sunny weather would be around 5 deg C warmer than an unstressed crop. Thus drought will through higher crop temperature, cause earlier senescence and lessen the radiation intercepted.

Salter and Goode (1967) reviewed many studies of cereal responses to soil moisture deficits and concluded that wheat and barley were most affected by SMD during the period from late shooting to flowering. However they also reported a number of studies which suggested that there were significant harmful effects on final yield caused by SMD at most stages of growth. A study by Day et al (1978) involving barley plot trials with both irrigation and artificially-induced drought produced results in general agreement with Salter and Goode. Final yield was related closely to total water use by the crop, and negatively to maximum potential soil moisture deficit when this exceeded 80 - 100 mm (the experiments were carried out at Rothamsted where maximum SMD's under cereals are around 180 mm). It was demonstrated that a higher sensitivity to maximum potential SMD occurred for crops subjected to drought up to the time of anthesis. The authors also analysed their results in conjunction with mean soil moisture deficits (D1, D2, D3, in mm) in the periods 1: tiller production and spikelet initiation, 2: end of initiation to anthesis, 3: post anthesis (roughly May, June and July in the year of the experiments), and showed that the quantities number of grains per ear (n1), number of ears per square metre (n2) and mean grain mass (m) showed high negative correlation with D1, D2 and D3 respectively, the relations being

$$n1 = 23.6 - 0.18D1 \qquad (3)$$

$$n2 = 8.4 - 0.21D2 \quad (\times 10^{-2}) \qquad (4)$$

$$m = 39.3 - 0.061D3 \quad (mg) \qquad (5)$$

The combined regression for grain yield was

$$yield = 6.74 - 0.033D1 - 0.013D2 - 0.0083D3 \ (t/ha) \qquad (6)$$

Equation (6) refers to a single variety (Julia) grown in a single year (1976) in one particular soil. It could presumably be modified for other varieties by multiplying the estimated yield by the ratio of the particular varieties' yield to that of Julia (using for example the yield data from NIAB trials), and modifying the coefficients associated with D1, D2, D3 linearly to account for different available water in other soils: for example the coefficient's would be doubled if the soil had half the available water. Equation (6) is of particular interest because it allows an element of forecasting of final yield. However it is not applicable outside the particular temperature and

radiation regimes experienced in 1976 and must be modified therefore to be used in other years. Some further results described by Day et al suggest how this might be done. They showed that a closely-linear relationship existed between water use by the crop from the beginning of May to harvest, and yield. This relation must depend on temperature also: it might be assumed that the effect of temperature is primarily in connection with the duration of growth of the crop. When the crop is unstressed throughout its growth then the yield would be proportional to accumulated potential transpiration. This is consistent with an analysis by Smith (1964) which demonstrated a good correlation between Regional barley yields in the South-West and potential transpiration: the South-West is an area with relatively high summer rainfall and in most of the 15 years considered the differences between potential and actual transpiration were probably small. The implication is that in any year the potential yield might be estimated from the potential transpiration over the period from say mid or late April to harvest, and then this yield modified in accordance with equation (6). The formal relationship might be written

$$\text{yield} = \frac{\text{yield (Pot)}}{\text{yield (max)}} \text{ (yield (max) } -aD1-bD2-cD3) \qquad (7)$$

where

yield (Pot) = potential yield in the particular year based on potential transpiration over the period to harvest.

yield (max) = maximum possible yield which could occur in any year (no water stress, high radiation, cool growing season).

Baier and Robertson (1967) analysed Maquis spring wheat years over 5 years from 8 experimental stations in Canada. The stations spanned a wide range of latitudes, with correspondingly large differences of average daily temperatures. Substantial negative correlations were found between yield and temperature in each month of the growing period, consistent with the idea that cool seasons favour high yield: the yields at stations with longer daylength were also generally higher. These results agree with growth chamber studies by Friend (1965) and Friend et al (1967) who found that high light intensity or low temperature resulted in high total plant weight and high spikelet number, and that increasing daylength increased the number of tillers and leaves. On this basis temperature is an important variable not just because it has a substantial control on green leaf duration, but also because it appears to have an effect on other factors important to final yield: thus higher temperatures produce higher respiration which would presumably adversely affect yield.

An assumption that winter wheat will respond in exactly the same way to weather as the spring-sown cereals is not justified, but differences may be small enough for temperature, radiation and soil moisture deficit to have rather similar effects on final yield.

Timeliness in sowing is important for high yields. Jarvis (1977) discussed this problem for winter wheat and spring barley and showed that for the latter

an average decline in yield of about 6% occurred for a 3-week delay from the optimum date of sowing (early March) with some acceleration of this decline for longer delays. Behavioural differences between varieties of winter wheat were rather larger but a yield loss less than about 5% was obtained for sowings confined to a period of about 35 days centred late September to early October. These last observations are broadly consistent with some results described by Croxall and Smith (1965).

The preceding discussions suggest that an initial analysis of regional cereal yields might be attempted in conjunction with the variables listed in Table 7. Temperatures during the establishment period of crops sown the previous

Table 7 Variables in regression analysis of yield data

Variable	Symbol used				
	March	April	May	June	July
Monthly mean air temperature (°C)	T1	T2	T3	T4	T5
SMD at end of month (mm)		S1	S2	S3	S4
Excess rain in month (mm)	E1	E2			
Sunshine (daily mean in hours)		U1	U2	U3	U4
Excess winter rain (mm)			X		
Area down to crop, expressed as departure from linear trend line (10^3 ha)			A		
Day of return to field capacity in previous autumn (1 = ≤ 1 September 76 = ≥ 15 November)			F		

autumn is unlikely to be limiting and has not been included therefore. Winter temperatures are probably rarely of significance in the main cereal growing areas. August temperature may be important in relation to harvest conditions but the factors leading to yield loss at harvest are complex and beyond the scope of a simple regression model. Rainfall is not included because its effects are usually indirect (through SMD or effect on plant disease: the latter cannot be treated here). March SMD's are assumed to be small usually and not significant. Excess rain in March and April (excess above field capacity) are included to indicate poor sowing conditions for spring crops, and are likely to be of more significance to barley than wheat yields. Sunshine is used as a substitute for photosynthetically active radiation in the main growing season. Excess winter rain provides an indication of loss of nutrients by leaching, although this may be of less importance in recent years because of adequate fertiliser applications in spring. Area down to the crop is included on the assumption that a larger than usual hectarage may include a higher proportion of lower-yielding land (in the case of barley this may not always be true: a high barley hectarage may be a consequence of a switch from winter wheat because of difficult autumn conditions, though again in recent years with better machinery it is usually possible to get the autumn sowings done). Finally the date of return to

field capacity will reflect to some extent the difficulties of cultivation the previous autumn and the likelihood therefore of damage to soil structure and consequent loss of yield.

3. Results and discussion

3.1 Wheat

The correlation coefficients between the yield departures and each of the variables in Table 7 are given in Table 8, for the full 24-year period and for the two 12-year periods. Some of these results appear to be inconsistent with the reasoning behind the choice of variables (§ 2). In particular the monthly soil moisture deficits are mainly positively correlated with yield. This may indicate merely that in most years wheat (which is predominantly autumn-sown) increases its rooting depth sufficiently rapidly in early spring to avoid damaging effects on yield due to moisture stress, and that relatively high SMD's indicate above-average transpiration and often a higher than usual radiation receipt. There is no conclusive evidence from the Table that higher temperatures reduce yield. On the other hand the results support the idea that high sunshine from May onwards is favourable to higher yields.

Table 8 Correlation coefficients between wheat yield departures over individual elements

Variable	West Midlands Region			East Region		
	1950–73	1950–61	1962–73	1950–73	1950–61	1962–73
S1	-.29	-.67	.25	0	.36	.17
S2	.08	-.04	.43	-.01	.07	.23
S3	.37	.37	.69	.04	.04	.36
S4	.41	.47	.58	.30	.49	.63
T1	-.33	.10	-.49	-.42	-.35	-.30
T2	-.03	-.03	-.19	.11	.29	-.16
T3	.28	.49	.49	-.08	-.13	.06
T4	.11	.40	-.10	-.40	-.26	-.57
T5	-.13	.09	.13	-.09	.40	.13
E1	.07	-.19	.22	.20	.24	.11
E2	.05	.28	-.04	.19	-.01	.09
X	-.05	.08	-.43	-.04	.11	-.16
U1	-.21	-.09	-.08	-.29	.45	-.40
U2	.21	.38	.32	.11	.25	.36
U3	.13	.23	.10	-.04	-.08	.07
U4	-.05	.28	.09	.03	.47	.19
A	-.04	-.14	-.01	.09	.07	.48
F	.21	.09	.34	.16	-.39	.23

Equation (1) was then evaluated using the variables in Table 7 in conjunction with a standard stepwise regression routine which tested at each step all the variables for significance: the variable which made the largest contribution to the reduction of variance of the yield estimates was then included in the final regression,

with the procedure being repeated at each step. Variables were rejected if their inclusion produced a reduction of variance corresponding to a f-value less than 0.5 (a partial correlation for the variables in question of about 0.2). Variables already included in the regression were tested at each subsequent step and rejected if the increase of variance on their removal corresponded to an f-value less than 0.4. The significant variables are listed in Table 9 with the f-values corresponding to each variable's removal, the coefficient values, and the multiple correlation coefficient.

Table 9 Significant variables in correlation analysis for wheat 1950 - 1973

West Midlands Region			East Region		
Variable	f-value to remove	coefficient value	Variable	f-value to remove	coefficient value
T1	13.3	-.070	T4	9.1	-.131
U1	9.4	-.109	T1	8.1	-.068
S2	8.9	-.0065	T2	7.0	.097
E2	7.3	-.011	U3	5.1	.060
S3	6.2	.0057	U1	4.5	-.110
T5	5.2	-.105	F	3.2	.0060
U2	4.9	.090	S1	1.2	.0038
X	3.1	.0001	X	0.4	-.0004
F	2.5	.0028			
T3	0.9	.032			
S4	0.4	.0015			
R = 0.91		Intercept = 1.40	R = 0.81		Intercept = 1.11

Only three of the significant variables are common to both regions. Climates in the two regions are generally fairly similar apart from slightly higher rainfall in West Midlands, and so a similar set of variables ought to describe much of the variation in yield in both regions. Figure 1 includes a plot of actual and predicted departures of yield for East Region. The extremes in 1962 and 1968 have not been well-fitted.

A similar analysis was performed for the years 1950 - 1961 and 1962 - 1973 using the trend lines appropriate to each period (Table 4). The variables chosen for the analysis were those found significant (f = 0.4) for each region in the 24-year analysis. Apart from X in 1950 - 1961 there was no significant variable among those chosen which was common to both regions (Table 10).

Table 10 Significant variables in correlation analysis of wheat yields in separate 12-year periods

Period	West Midlands Region			East Region		
	Variable	f-value to remove	coefficient value	Variable	f-value to remove	coefficient value
1950–1961	U2	1.7	.052	T2	8.7	.098
	E2	1.4	.0074	U1	7.5	.19
	X	0.6	-.0004	S1	2.8	.0056
				T4	1.3	-.047
				X	0.6	.0004
	R = 0.52		Intercept = -.29	R = 0.87		Intercept = -1.35
1962–1973	S3	21.3	.0092	T4	108	-.23
	U2	12.6	-.024	U1	85	-.30
	E2	11.1	.22	U3	48	.12
				X	10.5	-.0013
				S1	0.6	.0018
	R = 0.90		Intercept = -1.57	R = 0.98		Intercept = 4.06

Smith's (1964) demonstration (for barley) that yields may be closely correlated with accumulated potential transpiration when SMD's are small suggests that some improvement in correlation might be achieved by incorporating monthly PE in the list of variables. Table 11 shows correlations between yield departures and PE's in the months March - August (P1 - P6), and accumulated PE over the main growing season (April - July) (P7) and May - July (P8). The

Table 11 Correlations between wheat yield departures and PE

Variable	West Midlands Region			East Region		
	1950–73	50–61	62–73	1950–73	50–61	62–73
P1	-.38	.12	-.52	-.34	-.40	-.39
P2	-.26	-.10	.02	-.19	.31	.01
P3	.14	.36	.40	.14	.45	.24
P4	.08	.21	.18	-.23	-.11	-.07
P5	-.11	.20	.16	-.20	.37	.13
P6	.09	.27	.64	-.11	.29	.19
P7	.09	.37	.43	-.07	.34	.12
P8	.05	.42	.43	-.04	.33	.12

correlations for 1950–61 in particular support Smith's analysis to some extent, and the lower correlation in East Region is consistent with the increased effect of soil moisture deficit on yield in the drier eastern part of the country.

The stepwise regression analysis of yield was repeated therefore using as "independent" variables the soil moisture deficits S1 - S4, monthly mean temperature T1 - T5, date of return to field capacity F, excess winter rain X, and total potential evaporation for either April - July (P7) or May - July (P8): this set of variables would be anticipated to account for most of the expected yield variation, on the basis of preceeding discussions. The results of the analysis are given for the full 24-year period in Tables 12 and 13, in which are listed only those variables found significant.

Table 12 Correlation analysis for wheat 1950 - 1973: PE for April to July included

West Midlands Region			East Region		
Variable	f-value to remove	coefficient value	Variable	f-value to remove	coefficient value
S4	8.8	.0065	T1	7.2	-.072
X	8.0	-.0015	F	3.0	.0057
P7	6.4	-.0053	S4	2.8	.0030
F	2.9	-.0041	T4	2.5	-.061
S2	2.4	-.0031	T2	1.9	.059
T3	1.3	.032	T3	0.9	-.037
T1	1.2	-.022			
S3	1.2	.0026			
T4	.8	.027			
T5	.7	-.041			
R = 0.87		Intercept = 1.70	R = 0.72		Intercept = 0.56

Table 13 Correlation analysis for wheat 1950 - 1973: PE for May to July included

West Midlands Region			East Region		
Variable	f-value to remove	coefficient value	Variable	f-value to remove	coefficient value
S4	14.9	.0079	T1	7.2	-.072
P8	14.7	-.0100	F	3.0	.0057
X	7.9	-.0014	S4	2.8	.0030
T4	5.4	.061	T4	2.5	-.061
F	3.5	-.0045	T2	1.9	.059
T1	2.9	-.030	T3	0.9	-.037
S3	2.1	.0025			
R = 0.86		Intercept = 1.73	R = 0.72		Intercept = 0.56

The results confirm those of Table 11 for East Region where PE over the main growing season was negligibly correlated with the yield departures. The conclusions for West Midland where the correlations on P7 and P8 are negative are less clear. However the probable lack of homogeneity of the full 24-year sequence of yield data discussed earlier suggests that the importance or otherwise of PE in relation to yield should be explored using the 12-year data sets. The set of variables used in producing the results in Tables 12 and 13 is much too large to prevent overfitting when applied to 12 years of yield data but unfortunately the results from the tables give no useful indication of a smaller set of variables which might be used. Smith's (1964) study and Table 11 taken together suggest that PE for May to July, modified for the effects of soil moisture deficit which usually will be more important in the drier East, should account for a sizeable part of the yield variations over 12-year periods: a further analysis was therefore performed for these shorter periods using P8, S1 - S4 and also F and X, with the results given in Table 14. They are inconclusive and provide little evidence

Table 14 Correlation analysis for wheat yields over 12-year periods, including PE for May to July as an independent variable

Period	West Midlands Region			East Region		
	Variable	f-value to remove	coefficient value	Variable	f-value to remove	coefficient value
1950-1961	S1	9.0	-.0066	S4	43.7	.0082
	F	1.5	.0015	F	19.0	-.0155
	S3	0.7	.0008	X	13.2	-.0015
				S3	12.1	-.0049
				S1	9.2	.0061
				S2	3.1	-.0026
				P8	0.7	-.0009
	R = 0.77	Intercept = 0.0		R = 0.98	Intercept = 1.23	
1962-1973	S1	17.7	.044	S4	10.5	.0153
	S2	16.5	.014	P8	3.1	-.0091
	X	6.2	-.0011			
	P8	2.6	.0046			
	R = 0.94	Intercept = -1.95		R = 0.74	Intercept = 1.11	

for soil moisture deficits and potential evaporation controlling yields in the ways already anticipated.

3.2 Barley

Table 15 gives correlation coefficients between yield departures and all the "independent" variables (except F) used in the analysis for wheat.

Table 15 Correlation coefficients between barley yield departures and individual elements

Variable	West Midlands Region			East Region		
	1950–73	1950–61	1962–73	1950–73	1950–61	1962–73
S1	−.29	−.61	.24	−.03	.27	.34
S2	−.08	−.32	.16	−.22	−.13	−.05
S3	−.05	−.01	−.17	−.25	−.36	−.02
S4	.12	.34	−.08	−.25	−.20	−.13
T1	−.15	−.25	.33	−.18	−.53	.40
T2	.19	.05	.40	.09	−.23	.38
T3	.04	.38	−.09	−.20	−.23	−.15
T4	−.14	.07	−.55	−.32	−.44	−.38
T5	−.25	−.04	−.02	−.32	−.17	−.14
E1	.07	−.10	.25	−.02	−.37	0
E2	.06	.35	−.19	.13	−.12	−.10
X	.05	.27	−.46	−.04	−.06	−.10
U1	−.37	.02	−.47	−.17	.26	−.09
U2	.12	.11	.23	−.18	−.04	−.20
U3	−.24	−.20	−.56	−.28	−.46	−.17
U4	.01	.48	−.02	−.12	.30	−.28
A	.15	.44	−.34	.16	−.57	−.30
P1	−.10	.25	−.12	−.12	−.02	0
P2	−.32	−.21	0	−.11	−.12	.38
P3	.03	.04	.21	0	.09	.14
P4	−.28	−.19	−.55	−.49	−.09	−.32
P5	−.16	.41	−.20	−.43	−.09	−.28
P6	.04	.29	.33	−.28	−.23	.07
P7	−.31	.05	−.43	−.45	−.33	−.25
P8	−.26	.11	−.43	−.47	−.34	−.36

Comparing these results with those for wheat (Table 8 and 11) the yield of barley appears to be more sensitive to soil moisture deficit, and perhaps because of this generally inversely related to accumulated PE. There is some evidence that yield is decreased by higher temperatures in the main growing season. Table 16 gives the results from stepwise multiple regression, using the variables in Table 15 with the exception of those for PE.

Table 16 Significant variables (excluding PE) in correlation analysis for barley 1950 - 1973

West Midlands Region			East Region		
Variable	f-value to remove	coefficient value	Variable	f-value to remove	coefficient value
T5	16.2	-.172	T4	8.5	-.139
S4	9.9	.0046	T2	7.3	.173
E2	8.3	-.012	E2	6.4	.026
S2	6.1	-.0043	S1	5.3	.015
X	5.7	.0001	S4	3.7	-.0086
U1	4.6	-.064	X	3.3	-.0016
U2	2.2	.070	U1	3.0	-.133
U3	1.7	-.026	S3	2.5	.0068
E1	1.2	.002	U4	2.3	.095
			E1	2.0	-.0071
			A	1.7	.0023
			S2	1.1	-.0038
			T3	0.6	.047
R = 0.81	Intercept = 2.57		R = 0.79	Intercept = 0.49	

Four of the first eight significant variables are common to both regions but the regression coefficients of three of them have opposite signs in the two regions. The corresponding regression equations are unlikely therefore to have predictive value for years outside 1950 - 1973. A similar analysis was carried out for 12-year periods using the first 8 significant variables found from the 24-year analysis for each region; only two of the significant variables in the 12-year analysis were common to both regions in 1962 - 1973, and entirely different sets of variables emerged from the earlier 12-year period.

The analysis was repeated with the set of "independent" variables S1 - S4, T1 - T5, E1, E2, X and P8, for the 24-year period. The choice of this restricted list of variables follows from earlier discussions and limited evidence from Table A. The results are given in Table 17. The relatively small multiple correlation coefficients suggest that the regression coefficients have little relevance outside the 24-year period of data from which they were calculated. This may be partly the consequence of the discontinuity

Table 17 Correlations between 24-year barley yields and restricted set of "independent" variables

West Midlands Region			East Region		
Variable	f-value to remove	coefficient value	Variable	f-value to remove	coefficient value
S4	6.7	.0054	P8	6.3	-.0046
P8	2.1	-.0041	T2	1.7	.058
T5	1.8	-.062	E2	1.5	.0072
X	1.4	-.0004	S1	1.3	.0047
T2	1.3	.039	S2	0.7	-.0019
S3	0.6	-.0018			
R = 0.66	Intercept = 1.50		R = 0.57	Intercept = 0.73	

in the yield sequence at 1962 and the analysis was repeated for twelve-year periods, using now only P8, S1 - S4 and X in order to avoid overfitting (Table 18). The results provide little expectation of deriving useful

Table 18 Multiple correlations between 12-year barley yields and six "independent" variables

Period	West Midlands Region			East Region		
	Variable	f-value to remove	coefficient value	Variable	f-value to remove	coefficient value
1950-1961	S1	6.0	-.0052	S3	1.4	-.0020
				S1	0.7	.0034
	R = 0.61	Intercept = 0.0		R = 0.44	Intercept = .07	
1962-1973	S1	21.9	.042	P8	2.3	-.0069
	S2	17.3	.012	S1	2.2	.0093
	S3	4.1	-.0051			
	X	2.0	-.0005			
	P8	1.1	-.0034			
	R = 0.92	Intercept = 0.38		R = 0.55	Intercept = 1.68	

predictive relations for regional yields.

4. Concluding remarks

The preceding analyses have suggested that the published historical regional

cereal yields cannot be used to develop reliable regression relationships which might then be applied to the estimation of yields in the current season. The problem appears to be that published yields contain substantial year-to-year fluctuations which are not related to weather but rather to errors in estimation: thus the large increases in estimated yields in 1962 seem to be interpretable only in terms of a change in the method by which the yields were assessed. The analyses in this paper have taken no account of yield fluctuations caused by disease, and in some years these may have produced substantial reductions in yield, and have been a contributory cause of the failure of the analyses which have been described.

Disease control by chemicals is now very widespread, and regional yields in recent years have probably been less affected by disease than before. However these recent data do not provide a long enough sequence to use in regression analyses, and the problem of the reliability of the estimates of yield still remains. Progress in predicting yield departures in the current season will probably require the use of plot trials data from, for example, the NIAB variety trials in conjunction with a very limited range of predictors in order to develop the appropriate equations. Such an analysis has not been attempted here, but it might prove worthwhile to pursue it using initially perhaps only the total water use by the crop as the predictor. This will require an estimate of the duration of green leaf area but it seems likely that a simple method of obtaining this can be devised, based on accumulated temperature with some modification for elevation of leaf temperature caused by restricted soil moisture.

Any comments or suggestions on this paper should be referred to the authors.

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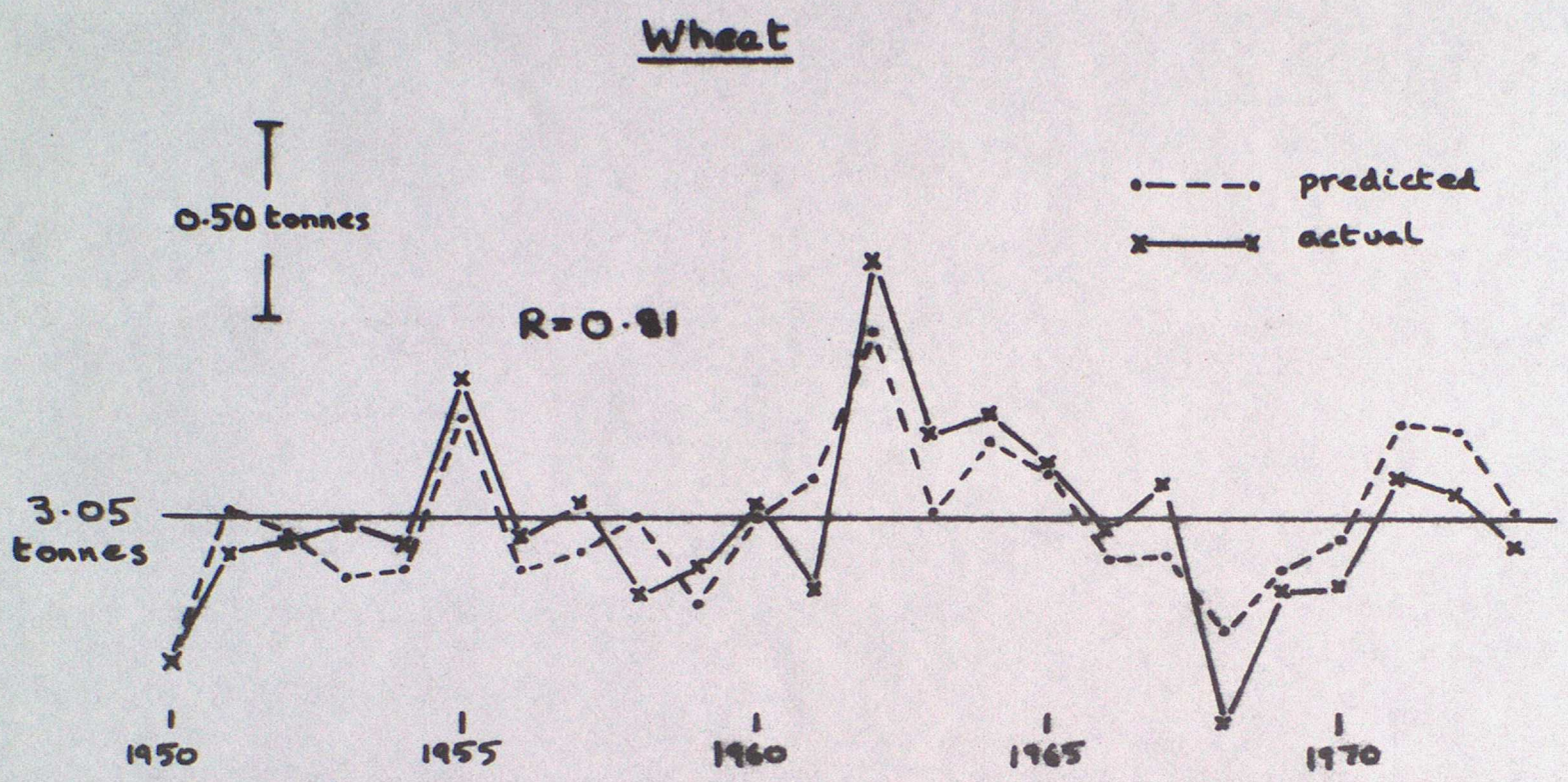

Figure 1 Actual and predicted departures of yield from trend, weighted to 1950 values, East Region

Appendix 1 Regional Cereal Yields 1950 - 1975

1. Wheat (tonnes/ha)

Year	SW	SE	Wales	W.Mid	E.Mid	E	Y/L	N
1950	2.16	2.42	2.08	2.54	2.68	2.67	2.73	2.52
51	2.50	2.40	2.45	2.60	2.73	3.02	2.69	2.61
52	2.51	2.55	2.48	2.63	2.86	3.11	2.93	2.86
53	2.77	2.82	2.60	2.91	3.00	3.21	3.09	2.92
54	2.32	2.60	2.35	2.55	2.78	3.23	2.80	2.66
55	2.81	3.19	2.86	2.78	3.15	3.76	3.54	3.17
56	3.01	2.83	2.51	2.98	3.05	3.38	2.99	2.97
57	2.90	2.84	2.56	2.84	3.16	3.54	3.20	3.12
58	2.99	2.92	2.54	2.95	2.87	3.34	3.10	3.02
59	3.48	3.38	3.06	3.24	3.57	3.78	4.00	3.68
60	3.40	3.36	3.16	3.44	3.56	3.73	3.69	3.36
61	3.61	3.40	3.33	3.39	3.54	3.53	3.70	3.76
62	4.23	4.23	3.71	4.21	4.27	4.63	4.26	4.11
63	3.54	3.67	3.55	3.86	3.93	4.16	3.79	3.85
64	4.13	3.85	3.82	4.11	4.39	4.29	4.34	4.35
65	3.84	3.86	3.73	3.98	4.11	4.20	4.15	4.17
66	3.64	3.59	3.31	3.66	3.84	4.04	3.77	4.06
67	3.83	3.95	3.97	3.95	4.27	4.25	4.46	4.41
68	3.60	3.27	3.85	3.36	3.58	3.48	3.88	4.10
69	4.40	4.28	3.97	3.86	3.66	4.01	3.92	4.17
70	4.35	4.22	4.00	4.24	4.05	4.09	4.30	4.68
71	4.25	4.20	4.10	4.25	4.40	4.55	4.43	4.39
72	3.66	3.84	3.78	3.87	4.31	4.55	4.40	4.10
73	4.39	4.53	3.85	4.34	4.20	4.41	4.20	4.20
74	4.57	4.61	4.08	4.73	5.06	5.09	5.22	5.37
75	4.05	4.11	4.14	4.19	4.39	4.41	4.46	4.56

Appendix 1 (continued)

2. Barley (tonnes/ha)

Year	SW	SE	Wales	W. Mid	E. Mid	E	Y/L	N
1950	2.02	2.21	1.82	2.43	2.40	2.52	2.57	2.51
51	2.56	2.37	2.25	2.53	2.53	2.56	2.54	2.73
52	2.45	2.38	2.41	2.56	2.61	2.36	2.80	2.95
53	2.74	2.73	2.54	2.76	2.79	2.88	3.00	2.56
54	2.42	2.57	2.17	2.67	2.58	2.91	2.56	2.66
55	2.84	3.21	2.57	2.83	2.97	3.19	3.70	3.35
56	3.11	2.85	2.32	2.88	2.86	3.05	3.04	3.19
57	2.89	2.53	2.45	2.58	2.81	2.78	3.15	3.14
58	2.85	2.87	2.38	2.85	2.63	2.97	2.81	2.94
59	3.32	3.24	2.90	3.17	3.14	3.15	3.74	3.75
60	3.06	3.11	2.89	3.29	3.11	3.09	3.39	3.72
61	3.51	3.13	3.12	3.28	3.18	3.03	3.54	3.50
62	3.68	3.63	3.35	3.65	3.39	3.62	3.86	3.89
63	3.22	3.40	3.36	3.65	3.57	3.67	3.72	3.77
64	3.51	3.48	3.53	3.75	3.73	3.74	3.95	3.92
65	3.38	3.67	3.53	3.77	3.84	3.93	3.92	3.82
66	3.31	3.39	3.45	3.59	3.62	3.69	3.61	3.51
67	3.52	3.59	3.61	3.74	3.88	3.65	4.12	4.00
68	3.27	3.22	3.64	3.45	3.52	3.37	3.64	3.63
69	3.84	3.90	3.68	3.39	3.28	3.54	3.46	3.59
70	3.25	3.24	3.25	3.43	3.09	3.06	3.39	3.74
71	3.67	3.64	3.94	3.92	3.66	3.33	3.85	3.83
72	3.56	3.81	3.85	3.90	4.00	4.07	4.08	4.31
73	3.84	3.95	3.98	3.92	3.85	3.88	3.96	3.91
74	3.61	3.81	3.74	4.05	4.09	3.75	4.29	4.39
75	3.23	3.12	3.41	3.28	3.22	3.41	3.43	3.93

(Acknowledgement is made to Mr G A Willis who calculated these regional yields from MAFF county statistics for production and acreage.)